

Final Report for “Study of Spin Splitting in GaN/AlGaN Quantum Wells”

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In the past year, we have finished the works as the schedule proposed. The result of our investigation can be separated into two parts. One is the study of HEMT made of AlGa_xN/GaN heterostructures, from the sample growth (by MBE) to the device process (by FIB), to investigate the spintronic device proposed by us. The other one is the study of GaN nanostructure, for example: GaN nanopillars, pyramids, and disks, grown on LiAlO₂ substrate by MBE. All of these results have been published in the international journals.

Part I: Characterization and application of AlGa_xN/GaN heterostructures.

(1) In the study of “Anomalous k -dependent spin splitting in wurtzite Al _{x} Ga_{1- x} N/GaN heterostructures”, **Physical Review B** **75**, 245307(2007), we have confirmed the k -dependent spin splitting in wurtzite Al _{x} Ga_{1- x} N/GaN heterostructures. Anomalous beating pattern in Shubnikov-de Haas measurements arises from the interference of Rashba and Dresselhaus spin-orbit interactions. The dominant mechanism for the k -dependent spin splitting at high values of k is attributed to Dresselhaus term which is enhanced by the Δ_{C1} - Δ_{C3} coupling of wurtzite band folding effect.

(2) In the study of “Dresselhaus effect in bulk wurtzite structures”, **Appl. Phys. Lett.** **91**, 082110, the spin-splitting energies of the conduction band for ideal Wurtzite materials are calculated within the nearest-neighbor tight-binding method. It is found

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14. ABSTRACT In the past year, the electronic properties of device-quality InGa_N/Ga_N and AlGa_N/Ga_N quantum wells were investigated by optical and transport measurements. Spin splitting of two-dimensional electron gas in Ga_N/Al_xGa_{1-x}N heterostructures were studied in detail. The result of the investigation can be separated into two parts. One is the study of HEMT made of AlGa_N/Ga_N heterostructures, from the sample growth (by MBE) to the device process (by FIB), to investigate the spintronic device proposed. The other one is the study of Ga_N nanostructure, for example: Ga_N nanopillars, pyramids, and disks, grown on LiAlO₂ substrate by MBE. All of these results have been published in international journals.					
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that ideal wurtzite bulk inversion asymmetry yields not only a spin-degenerate line (along the k_z axis) but also a minimum-spin-splitting surface, which can be regarded as a spin-degenerate surface in the form of $bk_z^2 - k_{||}^2 = 0 (b \approx 4)$ near the Γ point. This phenomenon is referred to as the Dresselhaus effect (defined as the cubic-in- k term) in bulk wurtzite materials because it generates a term $\gamma_{wz}(bk_z^2 - k_{||}^2)(\sigma_x k_y - \sigma_y k_x)$ in the two-band $\mathbf{k} \cdot \mathbf{p}$ Hamiltonian.

(3) In the study of “P-wave-enhanced spin field effect transistor and recent patents”, **Recent Patents on Nanotechnology** **1**, 169-175, (2007), we designed a P-wave-enhanced spin field-effect transistor made of AlGaIn/GaN heterostructure for the spintronic devices operated at high power and high temperature. The operation theory is based on the spin-polarized field-effect transistor designed by Datta and Das [Appl. Phys. Lett. **56**, 665 (1990)]. The mechanism of the p-wave enhancement in AlGaIn/GaN heterostructure was investigated. The recent development and related patents in the spin-polarized field-effect transistor were reviewed. In particular, we will focus on the recent patents which could enhance p-wave probability and control of spin precession of 2DEG in the AlGaIn/GaN transistor structure.

(4) In the study of “Spin splitting in $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ quasiballistic quantum wires” **J. Appl. Phys.** (2009), we have observed beating Shubnikov–de Haas oscillations in $\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ $[11\bar{2}0]$ -direction quantum wires grown on (0001) sapphire. The spin-splitting energy, (2.4 ± 0.3) meV for 200 nm wire, was suppressed to (1.2 ± 0.3) meV for 100 nm wire and smeared by the scattering from edge states and intersubbands. The spin splitting of Rashba effect can be used to control the differential phase shift of spin-polarized electrons when a gate bias is applied to a nanometer arm of quantum ring. Based on the results of spin-splitting for the $[11\bar{2}0]$ -direction $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ nanowire, the spin splitting of one-dimensional electron system in AlGaIn/GaN nanowire can be applied to a low-power consuming quantum-ring interferometer.

(5) In the study of “Spin-splitting in an AlGaIn/GaN nanowire for a quantum-ring interferometer”, **Appl. Phys. Lett.** **93**, 132114 (2008), An $\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ heterostructure was used to fabricate a ballistic nanowire with a wire width of 200 nm by focused ion beam. We observed the beating Shubnikov–de Haas oscillations in the nanowire with a spin-splitting energy of (2.4 ± 0.3) meV. Based on the results, we proposed a spin-Hall quantum-ring interferometer made of $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ nanowires

for spintronic applications.

Part II: Growth of GaN nanostructures:

(1) In the study of “Self-assembled *c*-plane GaN nanopillars on γ -LiAlO₂ substrate grown by plasma-assisted molecular-beam epitaxy”, **Jap. J. Appl. Phys.** **47**, 891 (2008), we have grown *M*-plane GaN films with self-assembled *C*-plane GaN nanopillars on a γ -LiAlO₂ substrate by plasma-assisted molecular-beam epitaxy. The diameters of the basal plane of the nanopillars are about 200 to 900 nm and the height is up to 600 nm. The formation of self-assembled *c*-plane GaN nanopillars is through nucleation on hexagonal anionic bases of γ -LiAlO₂. Dislocation defects were observed and analyzed by transmission electron microscopy. From the experimental results, we developed a mechanism underlying the simultaneous growth of three-dimensional *c*-plane nanopillars and two-dimensional *M*-plane films on a γ -LiAlO₂ substrate.

(2) In the study of “Line defects of *M*-plane GaN grown on γ -LiAlO₂ by plasma-assisted molecular beam epitaxy”, **Appl. Phys. Lett.** **92** pp.202106 (2008), we studied the microstructures of edge and threading dislocations of *M*-plane GaN epilayers grown on γ -LiAlO₂ substrate by high-resolution transmission electron microscope. We found that the edge dislocations were the *M*-plane GaN epilayer. We also observed a single stacking fault and found that the epitaxial strain was relaxed after the generation of stacking fault. The optical properties were evaluated by photoluminescence measurement at 77K and showed the variety of defect levels in the sample.

(3) In the study of “Self-assembled GaN hexagonal Micro-pyramid and micro-disk”, **Appl. Phys. Lett.** **94**, 062105 (2009). [\[This work was selected by the APL Editor for the Cover Image of Appl. Phys. Lett. 2009 February 09 issue.\]](#) The self-assembled GaN hexagonal micro-pyramid and micro-disk were grown on LiAlO₂ by plasma-assisted molecular-beam epitaxy. It was found that the (000 $\bar{1}$) disk was established with the capture of N atoms by most-outside Ga atoms as the (1 \times 1) surface was constructing, while the pyramid was obtained due to the missing of most-outside N atoms. The intensity of cathode luminescence excited from the microdisk was one order of amplitude greater than that from *M*-plane GaN.

References:

1. **Ikai Lo**, M. H. Gau, J. K. Tsai, Y. L. Chen, Z. J. Chang, W. T. Wang, J. C. Chiang, T. Aggerstam and S. Lourdudoss (2007), “Anomalous k -dependent spin splitting in wurtzite $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures”, **Physical Review B** **75**, 245307.

[Note: this paper was selected (by AIP Editor, David Awschalom) for the June 18, 2007 issue of Virtual Journal of Nanoscale Science & Technology, <http://www.vjnano.org>].

2. Wan-Tsang Wang, C. L. Wu, S. F. Tsay, M. H. Gau, **Ikai Lo**, H. F. Kao, D. J. Jang, J. C. Chiang, Meng-En Lee, Yia-Chung Chang, Chun-Nan Chen and H. C. Hsueh (2007), “Dresselhaus effect in bulk wurtzite structures”, **Appl. Phys. Lett.** **91**, 082110.

[Note: this paper was selected (by AIP Editor, David Awschalom) for the September 10, 2007 issue of Virtual Journal of Nanoscale Science & Technology, <http://www.vjnano.org>].

3. M.-H. Gau, **Ikai Lo***, W.T. Wang, J.-C. Chiang, and M.-C. Chou (2007), “P-wave-enhanced spin field effect transistor and recent patents”, **Recent Patents on Nanotechnology** **1**, 169-175, Bentham Science Publishers www.bentham.org (invited).

4. C.H. Hsieh, **Ikai Lo***, M.H. Gau, Y.L. Chen, M.C. Chou, W.Y. Pang, Y.I. Chang, Y.C. Hsu, M.W. Sham, J.C. Chiang, and J.K. Tsai, (2008), “Self-assembled c-plane GaN nanopillars on $\gamma\text{-LiAlO}_2$ substrate grown by plasma-assisted molecular-beam epitaxy”, **Jap. J. Appl. Phys.** **47**, p. 891. [Note: this paper was selected (by AIP Editor, David Awschalom) for the Virtual Journal of Nanoscale Science & Technology, <http://www.vjnano.org>].

5. **Ikai Lo**, C.H. Hsieh, Y.L. Chen, W.Y. Pang, Y.C. Hsu, J.C. Chiang, M.C. Chou, J.K. Tsai, and D.M. Schaadt (2008), “Line defects of M -plane GaN grown on $\gamma\text{-LiAlO}_2$ by plasma-assisted molecular beam epitaxy”, **Appl. Phys. Lett.** **92** pp.202106.

6. **Ikai Lo**, W.Y. Pang, Y.L. Chen, Y.C. Hsu, J.C. Chiang, W.H. Lin, W.T. Chiu, J.K. Tsai, and C.N. Chen, “Spin-splitting in an AlGaIn/GaN nanowire for a quantum-ring interferometer”, **Appl. Phys. Lett.** **93**, 132114 (2008).

7. **Ikai Lo**, Chia-Ho Hsieh, Y.C. Hsu, W.Y. Pang, Mitch M.C. Chou, “Self-assembled GaN hexagonal Micro-pyramid and micro-disk”, **Appl. Phys. Lett.** **94**, 062105 (2009). This work was selected by the APL Editor for the Cover Image of Appl. Phys. Lett.

2009 February 09 issue. [Note: this paper was selected (by AIP Editor, David Awschalom) for the 2009/2/23 issue of Virtual Journal of Nanoscale Science & Technology, <http://www.vjnano.org>].

8. Ikai Lo, Y. L. Chen, W. Y. Pang, Y. C. Hsu, Jih-Chen Chiang, C. C. Yang, and J. Y. Su, “Spin splitting in $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ quasiballistic quantum wires” **J. Appl. Phys.** (in press, 2009)